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Lunar Seismology

R. L. Kovach
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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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R. L. Kovach

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H. Trostle, *Acting Chief*
Research Analysis Section

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FOREWORD

This Report presents the results of a cooperative research program between the Seismological Laboratory, California Institute of Technology, and this Laboratory. The research at the Seismological Laboratory was supported by Contract No. NASw-81, sponsored by the National Aeronautics and Space Administration.

ABSTRACT

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A knowledge of the seismicity of the Moon will provide an insight into its thermal and tectonic history. Analyses of lunar seismograms from a simple passive experiment should give an estimate of the composition of the Moon and indicate its main internal structural features, such as the presence of a lunar crust and core. Meteor impacts will most probably be recorded by a lunar seismograph, even though the task of distinguishing such impacts from natural moonquakes may prove to be difficult. A single-axis seismometer will be carried aboard *Ranger 5*, and the data from any lunar seismic disturbances will be telemetered to Earth for subsequent analyses. More sophisticated active seismic experiments can contribute important information on the regional and local variations in the internal structure of the Moon and should rank high in priority for future lunar missions. Author

I. INTRODUCTION

Seismology has contributed greatly to our knowledge of the interior of the Earth. The presence of a crust, mantle, and liquid core have been demonstrated from seismological data, and even the simplest seismic experiments that can be conducted on the Moon will contribute basic information of great importance. Valuable clues concerning the interior of the Earth may be obtained when the Moon's internal structure is known. A knowledge of the seismic activity of the Moon is the key to its thermal and tectonic history.

In this Report the scientific results that can be obtained from a simple experiment involving one or more seismographs placed on the lunar surface are described. Because of promise of rich scientific rewards, the National Aeronautics and Space Administration will be implementing these seismic experiments as part of a lunar exploration program. A brief outline is given of the seismic experiment to be carried aboard *Ranger 5* and of future passive and active seismic experiments that will ultimately be employed on the Moon and planets.

II. SEISMICITY OF THE MOON

Even though the origin of earthquakes is not too well understood, the ultimate source of seismic energy is the Earth's initial temperature and its radioactively generated heat. For this reason, a measurement of the seismicity of the Moon will give the answer as to whether the Moon is a cold body or whether radiogenic heat is being formed in the Moon at the present time.

MacDonald (Ref. 1) has calculated the amount of stress buildup caused by internal heating for several assumed thermal models of the Moon and has shown that the greatest release of strain energy is at depths of 100–700 km in the lunar interior. If deeply buried radioactivity is assumed, then deep focus moonquakes are implied.

Extensive thermal calculations for the Moon have also recently been made by Kopal (Refs. 2–4) under the assumption that the sources of radiogenic heat (due to spontaneous disintegration of K^{40}, Th^{232}, U^{235}, and U^{238}) are uniformly distributed throughout the interior of the Moon in the same concentration as chondritic meteorites. These calculations show a steep nonuniform temperature gradient in the upper 100 km of the Moon and imply shallow seismic disturbances.

Earthquakes release from 10^{11} to 10^{26} ergs of energy and the smallest earthquakes are just detectable above the usual background noise. (A 1-kton nuclear explosion releases about 4×10^{19} ergs of energy.) Since the background noise on Earth is predominantly caused by meteorological disturbances such as wind and ocean-wave noise, the background noise or microseismic level is probably much lower on the Moon. A suggestion can be made that micrometeorite impacts and thermal noise comprise the lunar background noise.

Since the previously mentioned thermal calculations imply seismic activity on the Moon at least as high as that on Earth, about 10–100 moonquakes of sufficient magnitude to register on a single detector at any location on the Moon can be expected each month. Thus, a passive seismic experiment lasting 30–60 days on the Moon should give a good indication of seismic activity.

Topographic and geologic features associated with earthquake belts are not significantly present on the Moon; therefore, the method of lunar seismic energy release may be entirely different from that on Earth. A knowledge of whether moonquakes are localized in belts or are random in location, their correlation with any lunar topographic features, and their depth of focus are thus valuable clues for the thermal and tectonic history of the Moon.

III. ANALYSIS OF LUNAR SEISMOGRAMS

Since the data from a single seismic detector on the Moon are insufficient for deriving the travel times of seismic body waves, seismic wave velocity as a function of depth cannot be obtained. Theoretical travel-time curves can be calculated for several assumed lunar models to obtain a rough distance to the seismic source, since the main phases on a lunar seismogram will probably be identifiable. Travel-time curves for *P* and *S* waves for two assumed lunar models are shown in Fig. 1. Model II has a density distribution similar to that calculated by Jeffreys (Ref. 5) for the self-compression of a Moon composed of ultrabasic rock with a surface density near 3.28 gm/cm^3. Model III, which shows the effect of a heavy central core, has an extreme density distribution starting at 2.60 gm/cm^3 at the surface and increasing to 4.43 gm/cm^3 at the center of the Moon. Models II and III, which agree with the total mass of the Moon, are defined by the Roche Laws of Density Distribution.

$$\text{Model II:} \quad \rho = 3.415 - 0.135\,(r/R)^2$$

$$\text{Model III:} \quad \rho = 4.430 - 1.830\,(r/R)^2$$

The variation of compressional and shear velocity with depth was calculated from the empirical velocity-density relation based on Jeffreys' (Ref. 6) velocity distributions for the Earth and Bullen's (Ref. 7) density distribution.

$$\begin{aligned} \alpha &= -2.40 + 3.12\rho \\ \beta &= -0.60 + 1.52\rho \end{aligned} \qquad 2.5 < \rho < 4.5$$

Seismographs placed at different selenographic locations will ultimately allow seismic velocity to be derived as a function of depth. Once the velocity-depth function is known, the Adams–Williamson equation may be solved to give the density variation with depth within the Moon, assuming that there is no compositional change.

From the relative amplitudes of body and surface wave trains the coefficient of absorption of the lunar rocks can be found. Very rough estimates of seismic energy release can also be determined from studies of the amplitudes of body and surface waves. Deep focus moonquakes will be recognized by the small amplitude or absence of surface waves and the characteristic reduplication of principal body phases caused by reflections at the surface of the Moon.

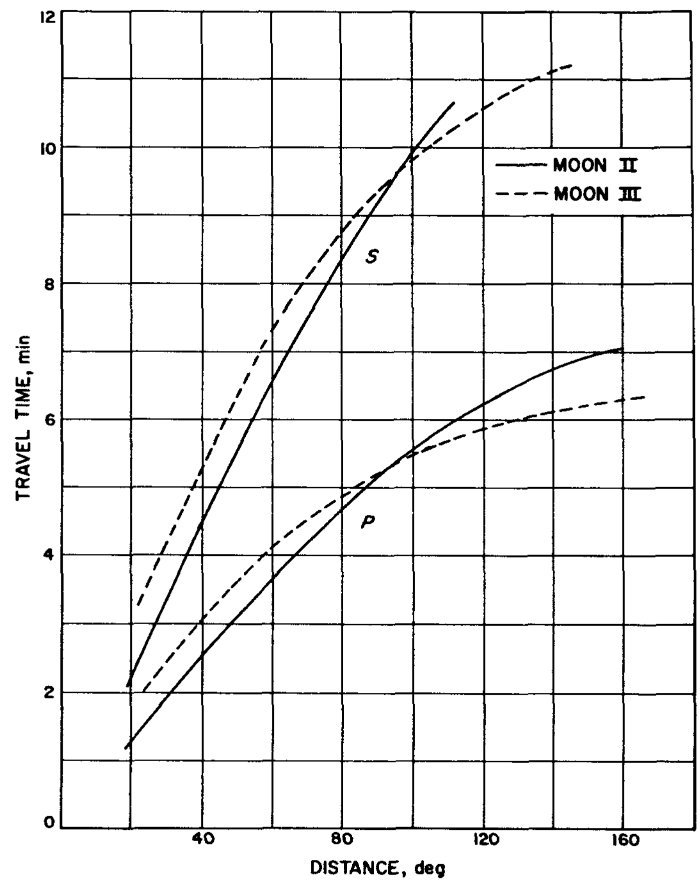

Fig. 1. *P* and *S* travel-time curves for two assumed lunar models

At epicentral distances of about 103–142 deg in the Earth the amplitude of *P* waves decreases sharply. This shadow zone is associated with the liquid core, which is also recognized by the absence of *S* waves. The *S* waves arriving at the core boundary do not enter the core but may be transformed into longitudinal waves in the core. Thus, a study of body-wave data on the Moon can give clues to the presence or absence of a solid or liquid core.

Press, Buwalda, and Neugebauer (Ref. 8) and Bolt (Ref. 9) have demonstrated that surface waves will be a powerful tool for exploring the Moon's outer layers. Love and Rayleigh wave trains are characteristically dispersed; their phase and group velocities are frequency dependent and are prescribed by physical properties of a wave guide caused by velocity and density variations with depth. Dispersion analysis of a lunar seismogram and comparison with theoretical dispersion curves computed for several assumed lunar models will yield the most probable structure for the outer layers of the Moon. Surface wave analyses on the Earth have demonstrated the presence of a low-velocity zone in the upper mantle and variations of crustal thickness between oceans and continents.

Figure 2 shows the complete spectrum of Love and Rayleigh waves for Moon Models II and III as calculated by Bolt (Refs. 9, 10) and Carr and Kovach (Ref. 11). Love and Rayleigh surface waves are related to the free torsional (toroidal) and spheroidal oscillations of the Moon. It is evident from an examination of these dispersion curves that observations of Love and Rayleigh wave trains on the Moon will allow a discrimination to be made between these strongly competing models. The absence or presence of a lunar crust analogous to that found on Earth has been shown to be readily detectable by dispersion analysis (Ref. 8).

One other aspect of surface wave dispersion on the Moon is shown in Fig. 2. The dashed curves are dispersion results calculated using a plane layer approximation to the lunar waveguide. The comparison between a plane layer approximation and one computed from spherical shells indicates that a plane layer approximation is inadequate for wave periods exceeding 25–30 sec. The total effect of curvature and gravity is to raise the phase velocity above that calculated from a plane layer approximation.

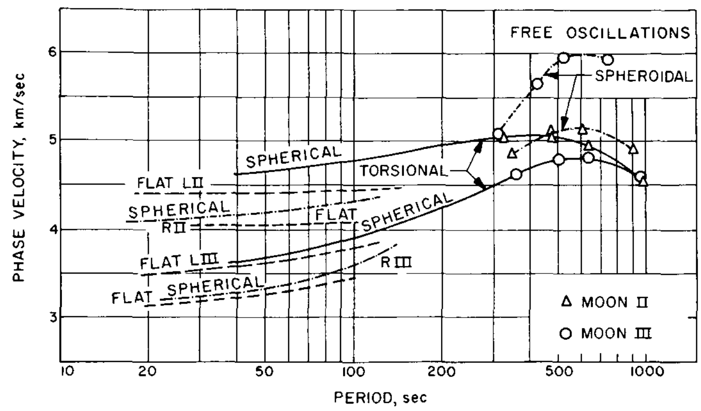

Fig. 2. Love and Rayleigh wave spectrum for Moon Models II and III

If the epicentral distance is not known on the Moon, surface waves can sometimes be used to obtain this distance. By measuring the difference in arrival times for surface waves of a given frequency which have traveled along the direct path and those that have completely circled the Moon, the distance to the shock can be deduced and a complete group velocity-dispersion curve can be obtained.

IV. METEOR IMPACTS

Unfortunately, the efficiency of seismic wave excitation by impact has not been studied, but it is reasonable to expect that large meteorites impacting the Moon could excite seismic waves. Only one documented meteorite fall on the Earth has excited seismic waves. On June 30, 1908 at 0 hr 15 min (± 3 min), a large meteorite fell in Siberia generating seismic waves which were recorded at four seismograph stations in central Europe (Whipple, Ref. 12; Tams, Ref. 13; Krinov, Ref. 14). At one station S(?) waves were recorded at an epicentral distance of 950 km, and only Rayleigh waves were recorded at the remaining stations at epicentral distances out to 5200 km, as would be expected.

It has been stated (Ref. 8) that the prediction of meteorite impacts which will generate seismic waves on the Moon is dependent on the following factors:

(1) The frequency of meteoritic impact as a function of meteoric mass.

(2) The energy released by such impacts and the efficiency of conversion to seismic energy.

(3) The attenuation of seismic waves with distance on the Moon.

(4) The threshold sensitivity of the recording instrument.

By utilizing Brown's estimates (Refs. 15, 16) of meteor impacts on the Moon and assuming that meteor impacts were as efficient as shallow nuclear explosions, estimates of seismically detectable meteorite impacts on the Moon were derived (Ref. 8). These estimates, shown in Table 1, indicate that meteorite impacts will quite probably be recorded by a lunar seismograph.

Table 1. Estimates of seismically audible meteorite impacts

Instrument threshold $m\mu$[a]	Attenuation in Moon	Detectable impacts/yr[b]
1	No attenuation; constant velocity	8.8 –26.5
	Absorptivity $= 10^{-4}\text{km}^{-1}$; Jeffreys-Bullen velocity	6.8 –20.4
	Absorptivity $= 2 \times 10^{-3}\text{km}^{-1}$; Jeffreys-Bullen velocity	0.37 – 1.1
10	No attenuation; constant velocity	0.75 – 2.2
	Absorptivity $= 10^{-4}\text{km}^{-1}$; Jeffreys-Bullen velocity	0.58 – 1.7
	Absorptivity $= 2 \times 10^{-3}\text{km}^{-1}$; Jeffreys-Bullen velocity	0.038– 0.11

[a] The *Ranger* seismometer has a threshold amplitude of about 2 $m\mu$ of ground displacement.

[b] These calculations have been updated in view of Brown's revisions (Ref. 16).

The task of distinguishing moonquakes from meteorite impacts may prove to be a task comparable to identifying earthquakes from nuclear explosions. However, it is believed that criteria can be developed which will allow an identification to be made. Several criteria might prove useful.

(1) The amplitude of seismic surface waves is dependent on the source depth.

(2) All compressions in the first motions of the principal phases may indicate an impact.

(3) Moonquakes may characteristically exhibit aftershocks.

(4) Moonquakes would be expected to be localized in belts.

Nevertheless, the problem may be extremely difficult if no characteristic signatures can be found on the lunar seismograms.

V. *RANGER* SEISMIC EXPERIMENT

As part of NASA's program, a single-axis seismometer was designed and fabricated by the Seismological Laboratory of the California Institute of Technology to be included as part of the scientific payload on *Ranger* 3, 4, and 5. The seismometer and associated telemetry electronics are mounted in a lunar capsule which will impact the lunar surface at a speed of several hundred feet per second. The landing capsule consists of a balsa-wood impact limiter with a survival sphere fluid-floated within. After lunar impact the survival sphere will erect itself using lunar gravity and will automatically align the axis of the seismometer in the direction of the local lunar vertical.

The seismometer, which weighs about 7 lb, contains a coil, a spring-suspended magnet, and an internal calibration device. An exterior view of a transparent working model of the seismometer is shown in Fig. 3. The seismic mass is a permanent magnet suspended from the body of the instrument by a helical spring and two cantilever spring rings. Concentricity of the seismic mass within the instrument body is provided by a spring ring, which permits the seismometer to operate at any inclination of its longitudinal axis. Movement of the coil, which is rigidly attached to the instrument body relative to the seismic mass, produces the transducer output. The seismometer is filled with a protective fluid to provide damping of the rapid movement of the seismic mass upon lunar impact. The seismometer has a natural period of about 1 sec and an output of 0.80 $\mu v/m\mu$ of ground amplitude (peak to peak deflection) at 1 cps. A more complete description of the seismometer has been given by Lehner, Witt, Miller and Gurney (Ref. 17).

After righting itself on the lunar surface the survival sphere will be punctured, allowing the seismometer caging fluid to evaporate. This reduction of pressure within the seismometer will activate its internal bellows-type pressure switch and a calibration pulser which will start the seismic experiment. Any lunar disturbances will then be detected and converted into electrical analog signals by the seismometer during the 30–60 day lifetime of the lunar capsule.

The lunar capsule contains the necessary electronics for amplifying the electrical analog signals and transmitting the seismic data back to Earth. A pass band of 0.05–5 cps and a dynamic range of 20 db can be accommodated by the transmitter. Since the amplifier will allow a dynamic range of 30 db, the analog signal will be logarithmically compressed before telemetering to Earth. This compression will be removed at the ground receiver on Earth and the original dynamic range of the signal will be restored.

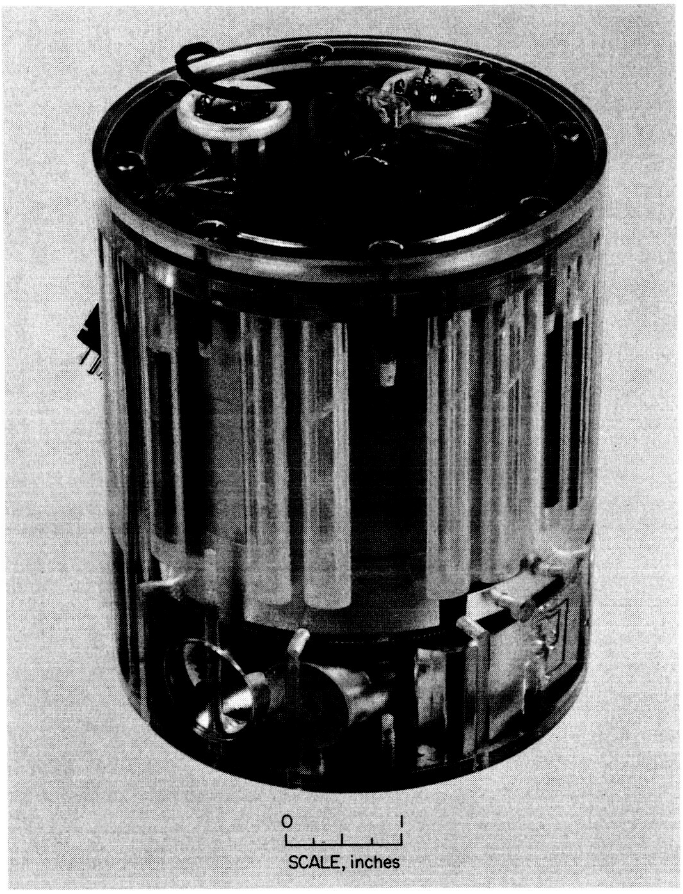

Fig. 3. A plastic model of the *Ranger* seismometer

The amplified signal will modulate the subcarrier frequency of a voltage-controlled oscillator. This frequency-modulated signal will then phase modulate a 960-Mc RF carrier (Fig. 4) which will be received alternately by the three Deep Space Instrumentation Facilities (DSIF) of the Jet Propulsion Laboratory. The necessary electronic equipment will be utilized to recover the same analog signal that was used to frequency-modulate the subcarrier and expand the signal to its original 30-db dynamic range.

Before the seismic information can be analyzed, it is necessary to pass the signal through compensation filters

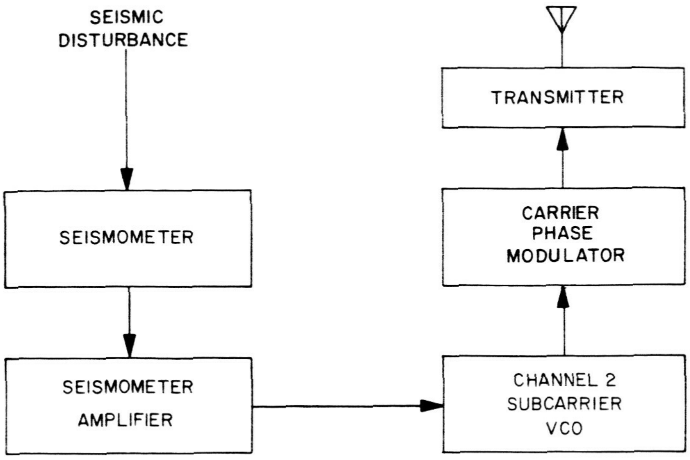

Fig. 4. Seismic data transmission

so that the data are similar to those obtained from familiar seismograph systems. Those seismographs which will be simulated are the Benioff short-period seismograph (seismometer period, $T_o = 1$ sec; galvanometer period, $T_g = 0.2$ sec) and the Benioff long-period seismograph ($T_o = 1$ sec; $T_g = 90$ sec). For the simulated short-period instrument a low-pass RC filter having attenuation-vs-frequency characteristics analogous to a galvanometer of 0.2-sec period will be used; for the long-period instrument a filter with the response of a 90-sec galvanometer within the 0.05–5 cps band pass is necessary. After passage through the compensation filters, the signal will be amplified for input to a direct-writing drum recorder.

An over-all systems test was conducted to examine the quality of seismic data obtained after transmission through the telemetering system. A lunar seismometer which was modified for use in the Earth's gravitational field was placed on Mt. Wilson, California, and a precision FM recorder was used to record random seismic disturbances. These seismic signals were then transmitted from the collimation tower to the antenna at the DSIF Goldstone Tracking Station using an electronic equivalent of the lunar capsule. The signal obtained after passage through the system was then compared to the original seismic signal, and the quality of data obtained from the system proved to be excellent (Fig. 5).

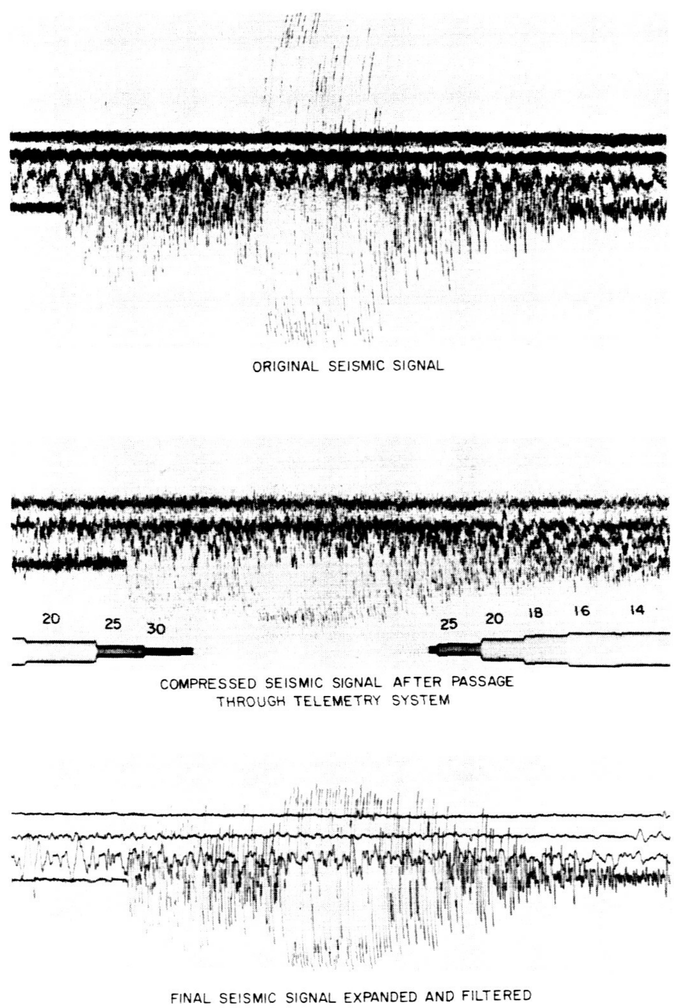

Fig. 5. Quality of seismic data after passage through telemetry system

VI. FUTURE SEISMIC EXPERIMENTS

A short-period seismometer is an excellent selection for use on early stages of Moon exploration because of its reliability, ruggedness, and good over-all response to short-period seismic waves. For future lunar missions it is planned to soft-land spacecrafts on the Moon which will contain three-component long-period seismometer systems, oriented to give three mutual perpendicular components of ground motion. A three-component long-period seismometer can be used to determine azimuth of approach of surface waves and will provide long-period surface-wave and free-oscillation data. However, a long-period seismometer is inherently more delicate than a short-period instrument. Ideally, it is hoped that a minimum of three seismograph stations containing both short- and long-period seismometers can be placed at different locations on the Moon so that the question of seismic selenography can be firmly established.

Active seismic experiments, such as seismic reflection and refraction techniques, will ultimately be employed on the Moon and planets. Seismic refraction surveys can be used to detect regional and local variations in the internal velocity structure of the Moon, and many geological problems on the Moon can be logically attacked with active seismic experiments. If the Moon should prove to be aseismic, then active seismic experiments must be used to obtain valuable information concerning the interior of the Moon.

Watson, Murray, and Brown (Refs. 18, 19) recently pointed out that local concentrations of ice may be present on the Moon and may even be exposed on the surface in permanently shaded areas. In the near-surface layers of the Moon, beneath the effect of the diurnal heat wave, a layer of ice may also be present (Ref. 4). Controlled active seismic surveys could be used to detect the presence of ice layers on the Moon.

The amount of compaction with depth in any thick lunar dust layer and the nature and extent of any lava or ash flows can be profitably investigated with active seismic measurements. Other geological problems awaiting solution with sophisticated seismic experiments are the subsurface relations of the maria and highlands, the existence and nature of isostatic compensation of lunar topographic features, and the origin and extent of the domes and ridges in the maria.

Since the effect of pressure will be small in the upper layers of the Moon, there is a possibility that the temperature variation with depth may be derivable from the data obtained from careful seismic velocity surveys.

Preliminary calibration experiments for future lunar explosion surveys have been conducted on a variety of materials that might reasonably be found on the Moon to determine ground amplitudes vs explosive yield and ground-amplitude falloff with distance for various types of explosives and charge configurations. The drilling of shot holes will not initially be feasible on the lunar surface, so measurements were made for surface-detonated charges. Because of the probable lower background noise level on the Moon, smaller explosive charges will be necessary than on Earth. Preliminary results indicate that a 1-lb explosive charge will be adequate for a 2000-ft seismic profile. A 2000-ft seismic profile is within the capability of unmanned local experiments that can be conducted on the Moon, but longer profiles will be required for deeper depth penetration. A manned or a remote-controlled roving-vehicle experiment will eventually be needed for long seismic profiles.

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